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The Automatic Telescope Network

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Abstract

Because of the scheduled GLAST mission by NASA, there is strong scientific justification for preparation for very extensive blazar monitoring in the optical bands to exploit the opportunity to learn about blazars through the correlation of variability of the gamma-ray flux with flux at lower frequencies. Current optical facilities do not provide the required capability. Developments in technology have enabled astronomers to readily deploy automatic telescopes. The effort to create an Automatic Telescope Network (ATN) for blazar monitoring in the GLAST era is described.

1. Introduction

The EGRET γ -ray telescope aboard the *Compton Observatory* has detected ~ 1 GeV emission from ~ 70 blazars (Hartman *et al.* 1999, Mattox 1999a). The apparent γ -ray luminosity seen for the EGRET blazars is as much as one hundred times larger than that at all other wavelengths for some flaring EGRET blazars. Variability of the γ -ray flux from some blazars on a time-scale as short as 4 hours has been observed (Mattox *et al.* 1997). This implies that the region of γ -ray emission must be very compact. Because the opacity for γ -ray to $\gamma - \gamma$ pair production with x-rays must not prevent γ -rays from escaping, relativistic beaming with a Lorentz factor of ~ 10 for the bulk of material in the jet is required (Mattox *et al.* 1997). This conclusion is reinforced by the observation of a high x-ray state during the 1996 γ -ray flare of 3C 279 (Wehrle *et al.* 1998) which implies that the x-rays originate in the same volume as the γ -rays). With substantial accretion onto a $\sim 10^8 M_\odot$ blackhole, there is sufficient power to create the relativistic jets. However, the physics involved in the conversion of gravitational potential to kinetic luminosity is not understood.

It is widely believed that this GeV emission is due to inverse-Compton scattering by shock-accelerated leptons within the relativistic jet. However, there is disagreement over the origin of the ~ 1 eV photons which are scattered. Some modelers believe that they originate in the synchrotron emission of the leptons, so the γ -rays are a result of the synchrotron self-Compton (SSC) process (Bloom & Marscher 1993).

Another possibility is that the low energy photons come from outside of the jet. This is designated as the external Compton scattering (ECS) process. Dermer, Schlickeiser, & Mastichiadis (1992) suggested that they come directly from an accretion disk around a black hole at the base of the jet. It was subsequently proposed that the dominant source of the low energy photons for scattering

could be due to re-processing of disk emission by broad emission line clouds (Sikora, Begelman, & Rees 1994).

The correlation of optical, x-ray, and γ -ray emission is expected to provide a definitive test of these models. If the variation in the synchrotron flux is due to a change in the electron density, the SSC emission, which depends on the second power of electron density, will be observed to vary quadratically in comparison to the synchrotron with no lag (for a single homogeneous emission zone). If the high-energy emission is ECS due to reprocessed in the broad line region before inverse Compton scattering (Sikora Begelman and Rees 1994), the ECS flux will lag the optical disk flux by at least 1 day if the ECS flare is due to increased optical emission from the disk. If the ECS flare is due to an enhancement in the relativistic particle content of the jet, the optical and γ -ray flux will vary in a linear fashion with no lag if the optical synchrotron and ECS emission occur in the same region of the jet. Ghisellini & Madau (1996) suggest that the dominant source of low energy photons for ECS scattering is broad-line-region re-processing of jet synchrotron emission — the “mirror model”. In this case, there could be linear correlation between synchrotron emission and ECS emission with a γ -ray lag of $\sim 2 \times 10^3$ seconds, if jet plasma entering a region of enhanced magnetic field resulting in more synchrotron emission, and the re-processing region was $\sim 10^3$ light-seconds away. In this scenario, a change in the synchrotron emission spectrum would occur, and could be discerned with accurate photometry in multiple optical bands (e.g., B and R). Thus, good sampling of multiple energy ranges offers the opportunity to distinguish models for the continuum emission of blazar jets.

As we gain understanding of this emission, it potentially can then be used to study the origin of the jet. In addition to providing for discrimination between models, simultaneous multiwavelength observations also have the potential to determine of properties of the jet; e.g., Takahashi *et al.* (1996) infer the strength of the magnetic field in the jet of blazar Mrk 421 by examining the rate of Synchrotron energy losses with the ASCA satellite.

NASA’s GLAST mission, the next generation GeV gamma-ray telescope, will provide excellent GeV sensitivity. It is currently scheduled to be launched in 2005 and to operate for a minimum of 5 years. NASA’s URL for GLAST is <http://glast.gsfc.nasa.gov>. A simulated blazar GLAST light curve is shown in Figure 1 for PKS 1622-297 (which produced the largest point source flux observed by EGRET, Mattox *et al.* 1997). Compared to EGRET, a dramatic enhancement in the γ -ray light curve resolution due to the increased aperture of GLAST is apparent.

2. The Optical Monitoring of Blazars in the GLAST Era

If the γ -ray luminosity function of blazars is roughly similar to the radio luminosity function of the parent population of extragalactic flat-spectrum radio sources as often assumed (e.g., Stecker and Salamon 1996), GLAST will detect ~ 5000 blazars. To observe just 20% of this population in the optical band just once per month will require 33 observations per day. For the expected magnitude distribution (~ 14 to ~ 24 — deduced from the distribution of the V magnitudes given by NED for robust 3EG EGRET identifications, Mattox 1999a), a telescope of at least ~ 1 m aperture will be required for many of these sources. Assuming an average of 10 minutes to set up, expose, and read-out for each observation, 80% of all available time with a 1m class telescope will be required for just monthly monitoring.

Since γ -ray variability was observed with EGRET on sub-day time scales, (see Figure 1), more

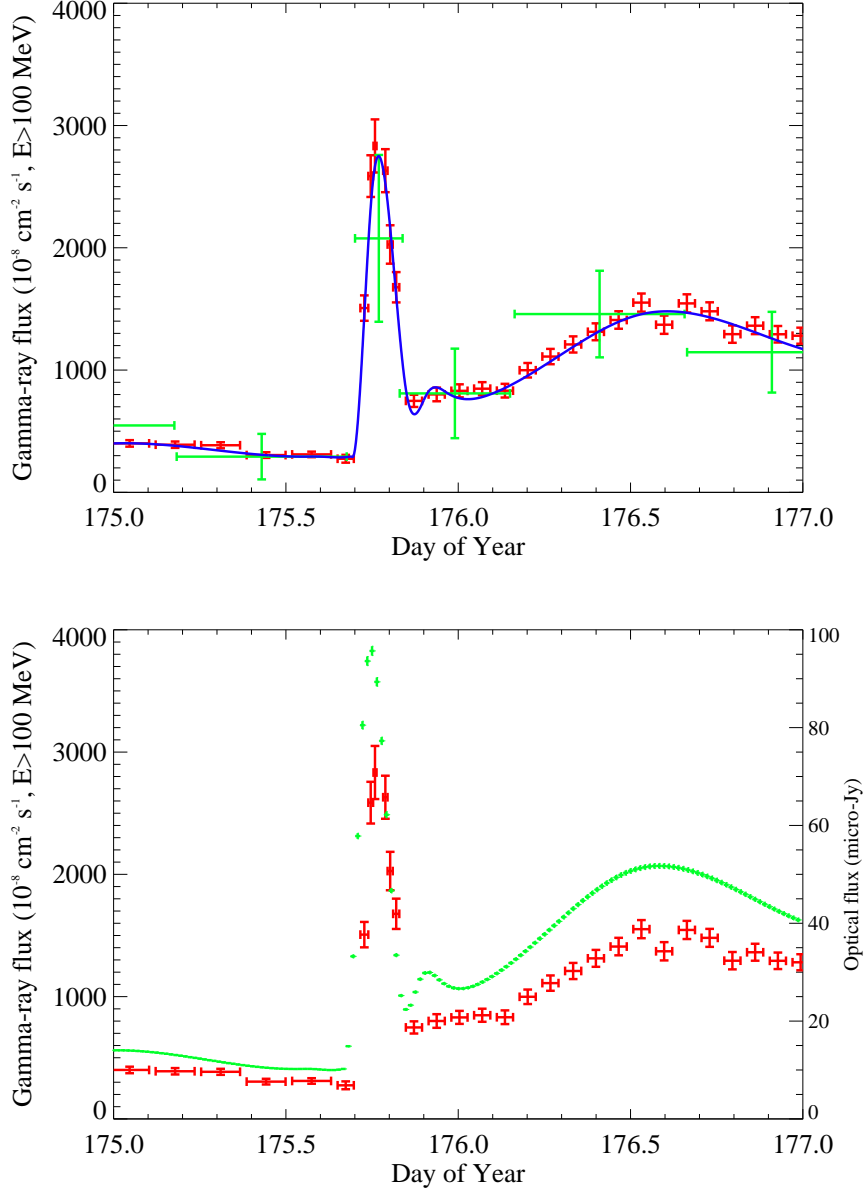


Fig. 1.— The figure on top shows the measured EGRET flux for PKS 1622-297 (Mattox *et al.* 1997) with the large error bars [green in a color rendition]. The solid [blue] line is a plausible hypothesis for the actual flux. Assuming this flux, simulated GLAST measurements are shown with much smaller error bars [red]. The figure on the bottom shows the simulated GLAST measurements [red] along with simulated ATN optical observations [green]. It is assumed that the γ -ray flux varies linearly in relationship to the optical with a lag of 2000 seconds. The optical observation interval is 30 minutes.

frequent monitoring is appropriate for bright sources which will produce sufficient GLAST counts to be more rapidly resolved. Table 1 specifies the required density of optical monitoring based on the number of sources which are expected to be time resolved by GLAST on a timescale shorter than ~ 10 days. The average number of optical observations is 222 per day, and requires four 1m class telescopes at a variety of longitudes. The prospect of making an average of 222 optical observations per day for the duration of the GLAST mission (4×10^5 observations over 5 years) provides a strong incentive to consider the use of automated, ground-based telescopes.

This monitoring could be accomplished from space by a single facility with capabilities similar to the Hubble Space Telescope. However, the construction of four 1m class telescopes on the ground can be accomplished for a cost ~ 2 orders of magnitude less than a space telescope with HST capabilities.

In addition to the γ -ray flux, Figure 1 shows simulated high-temporal-density optical observations. It was assumed that the γ -ray flux varies linearly in relationship to the optical with a lag of 2000 seconds, consistent with the “mirror model” for γ -ray emission. The linear dependence and the lag are both clearly resolved. Thus, we can expect that dense optical sampling in conjunction with GLAST observations will produce a very good opportunity to test blazar models in detail. Because PKS 1622-297 is a 20th magnitude source, a network of ~ 1 m telescopes would be required to obtain this data. Although a large multiwavelength campaign was organized for 3C 279 in 1996 (Wehrle *et al.* 1998) which explicitly included over 20 optical observers, only one optical observation was obtained in the 3 days of maximum γ -ray flux. Without extensive preparation prior to the GLAST mission, more extensive optical coverage may not be available during the GLAST mission.

3. Automatic Telescopes

The automatic operation of optical telescopes began with a 50-inch telescope on Kitt Peak. This telescope was constructed with NASA funding as the Remotely Controlled Telescope (RCT). The initial intention was to develop techniques for controlling telescopes in space. It was soon apparent that this was not a useful approach to learning to control a space telescope — the dynamics were very different, as were the scales of the budgets (personal communication, Steve Maran, 1999).

Obs. interval	Obs. duration	Fraction	Number of sources	Obs./day	Telescopes required
Monthly	10 min.	0.2	1000	33	0.8
Weekly	10 min.	0.05	250	36	0.9
Daily	7 min.	0.01	50	50	0.8
2 hours	5 min.	0.001	5	60	0.7
5 minutes	5 min.	0.00003	one 15% of the time	288 (ave. 43)	0.5
Total				222	3.7

Table 1: Optical monitoring required during the GLAST mission. An average of 7 clear dark hours for each ~ 1 m telescope is assumed for each diurnal interval. A measurement in two optical bands (i.e., B and R) could routinely be made for sufficiently bright sources in the specified observation interval to ascertain the spectral slope.

The RCT telescope focus then shifted to an attempt to demonstrate the operation of an automated telescope — something which the Whitford Committee suggested in 1964 as a means to enhance the productivity of small telescopes (Maran 1967). A decade of effort resulted in one astronomical paper (Hudson *et al.* 1971), and the realization that a human telescope operator was much more cost effective than telescope automation with the technology available in 1969 (personal communication, S. Maran, 1999).

During the 3 decades which have transpired since the RCT telescope experiment, remarkable advances in technology have occurred. Modern technology now makes telescope automation straight forward. It is likely that vision of the Whitford Committee of substantial gains in productivity through the automation of telescopes may soon be realized. The most important technological advances have been: (1) the development of powerful, reliable, inexpensive, and compact computers; (2) the development of intelligent controllers for mechanical motions; (3) the development of charge coupled devices (CCDs), and (4) the accumulation of experience in the most effective ways to control and use fully automated and unattended observatories.

A telescope equipped with servo motors and rotation encoders on both axes, and driven by a computer with an accurate model of telescope flexure and pointing aberrations, can point anywhere on the sky with an open loop accuracy of $<10''$. Thus, source acquisition is straightforward, and easily automated. The CCD camera has liberated astronomers from the drudgery of the darkroom, and the anguish of the interpretation of non-linear photographic media. The CCD based camera produces digital data with linear response, and with a quantum efficiency as high as $\sim 90\%$, two orders of magnitude better than photographic film. Also, CCDs can provide simultaneous measures of sky brightness and comparison star brightness, which permits accurate differential photometry even with a partly cloudy sky.

A number of groups are operating automatic telescopes and some are developing plans for networks of automatic telescopes (hypertext links to those with web pages are maintained at http://gamma.bu.edu/atn/auto_tel.html). At least three manufacturers have designed telescopes of aperture 60 cm or larger which are capable of automated operation, Torus Technologies and DFM in this country, and TTL in England.

A coordinated network of automated telescopes at diverse sites will facilitate optical monitoring of selected GLAST sources on sub-day timescales, a task which is not otherwise routinely feasible — although we have done this experimentally with a miniscule duty-cycle with the Whole Earth Blazar Telescope (WEBT) which is described in a separate paper in this volume (Mattox, 1999b). The ATN project has been undertaken to promote the development of a network of automated telescopes to support blazar monitoring. A web site has been established at <http://gamma.bu.edu/atn/> to coordinate effort, and disseminate information.

4. Automatic Telescope Standards

Much remains to be done in the realm of software before automatic telescopes can execute a program such as the GLAST blazar monitoring. There are currently no standards in place for automated telescopes, to permit them to be used coherently.

Therefore, an international working group is in formation to work with the IAU Commission (number 9) on Instruments to develop standards for automatic telescopes. The web site is <http://gamma.bu.edu/atn/standards/>. These standards will expedite the creation and utilization

of networks of telescopes for science and education.

The existence of a standard command set will form an interface between a telescope specific TCS (Telescope Control System) and a higher level Observatory Control System (OCS). This will promote the development of telescope-independent OCS software, which will provide for instant robotocization of additional new and refurbished telescopes which comply with the TCS standard.

The standards will also include appropriate protocol for Internet control of automatic telescopes. The existence of such a standard protocol will promote cooperative development and utilization of networks of robotic telescopes. A standard protocol for Internet control will facilitate cooperative utilization of these telescopes. This will provide for the utilization of more diverse facilities by all participants, increasing the range of projects possible, and the efficiency of telescope utilization.

5. Other Scientific Applications of the Networks of Automatic Telescopes

It is also expected that networks of automatic telescopes will be useful for studying other transient phenomena, e.g., binary stellar systems, gamma-ray bursts, quasar/galaxy lensing systems, microlensing events, and asteroseismology. A network which is sized to provide observing time for other areas of investigation will include more telescopes. Therefore, it will be more efficiently scheduled, and will provide better multi-longitude coverage for blazars, and gamma-ray burst follow-up. Therefore, it is of interest to collaborate with other astronomers who can use automatic optical telescopes.

Automatic telescopes can also serve as a very valuable facility for science education. A network of automatic telescopes is being proposed by the Hands-On Universe Project (<http://hou.lbl.gov/>) to provide abundant, high-quality, CCD data for education. The possibility of integrating blazar monitoring into this effort is being explored.

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